

Short Duration Voltage Sags Can Cause Disruptions

This Power Note is about what causes voltage sags, their impacts and possible solutions.

A voltage sag is a short duration (i.e., 0.5-60 cycles) decrease in the rms voltage magnitude, usually caused by a fault somewhere on the power system (*Figure 1*). Voltage sags are the most important power quality problem facing many industrial customers especially those with a process. Equipment used in modern industrial plants (process controllers, programmable logic controllers, adjustable speed drives, robotics) is actually becoming more sensitive to voltage sags as the complexity of the equipment increases. Even relays and contactors in motor starters can be sensitive to voltage sags, resulting in shut down of a process when they drop out.

It is important to understand the difference between an interruption and a voltage sag. An interruption is a complete loss of voltage whereas a sag is when the voltage drops below 90% of nominal. Interruptions occur when a source-side protective device opens a section of the circuit due to a fault condition. The interruption may be sustained or momentary. Sustained interruptions last minutes or hours while momentaries last a few seconds. The voltage sag lasts only as long as it takes the protective device to clear the over-current condition, typically up to 10 cycles (one cycle is 16.7 milliseconds). The range in seconds then is roughly 0.001 to 0.167 seconds (about the range of a blink of an eye). A person can in many cases see the lights blink during these events.

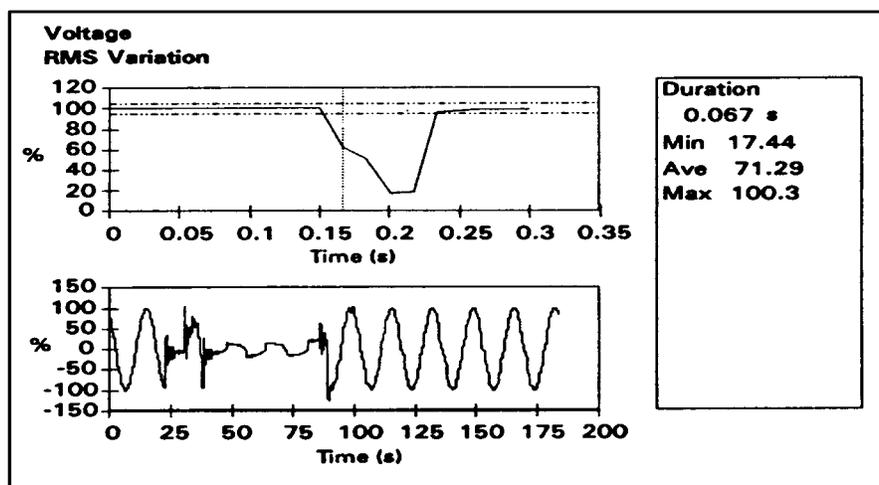


Figure 1. - Voltage Sag Waveform Caused by a Remote Fault Condition (4 cycles)

A sag is when the magnitude of the voltage is reduced below 90% for 0.5-60 cycles during a fault occurring somewhere nearby. Systemwide, an urban customer on average may see 1 or 2 interruptions a year whereas the same customer may experience over 20 sags a year depending on how many circuits are fed from the substation. Why are there more sags than interruptions? Most substations have multiple transformers and multiple circuits per transformer. When a fault occurs on one circuit, the supply voltage is depressed in the substation, thereby affecting many circuits not just the one where the fault occurs. Depending on the stiffness of the transmission system, other substation banks and even other substations can be affected. In addition, many breakers operate multiple times clearing the same fault.

Within a customer premise, there are other reasons for the voltage to be depressed such as an internal fault or a large load starting. Typically, motor starts last for longer than 30 cycles but very minimally reduce the voltage if adequate design requirements are met. Both of these internal conditions however can cause the lights to flicker just as a utility sag does.

Utility system faults can occur on the distribution system or on the transmission system. *Figure 2* illustrates a typical distribution system configuration with a number of feeders (circuits) supplied from a common bus. A fault on Feeder F1 will cause an interruption to customers downstream from the protection device that operates on that feeder. However, all of the customers on all four parallel feeders will experience a voltage sag until the protection device clears the fault current.

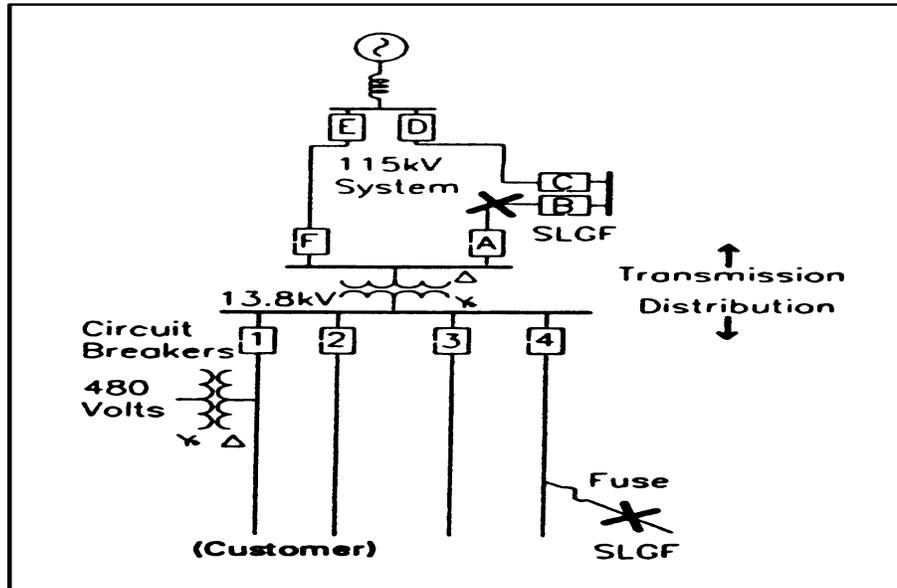


Figure 2. - Typical Distribution System One Line.

With reclosing breakers at the substation or along a feeder, the customers on parallel feeders can experience as many as three voltage sags in succession, with durations ranging from a couple cycles to more than ten cycles (see typical reclosing sequence in *Figure 3*). Sags are also caused when a fuse opens due to a fault. Current limiting fuses operate much faster than a breaker, so the resultant sag is shorter in duration, *figure 4*.

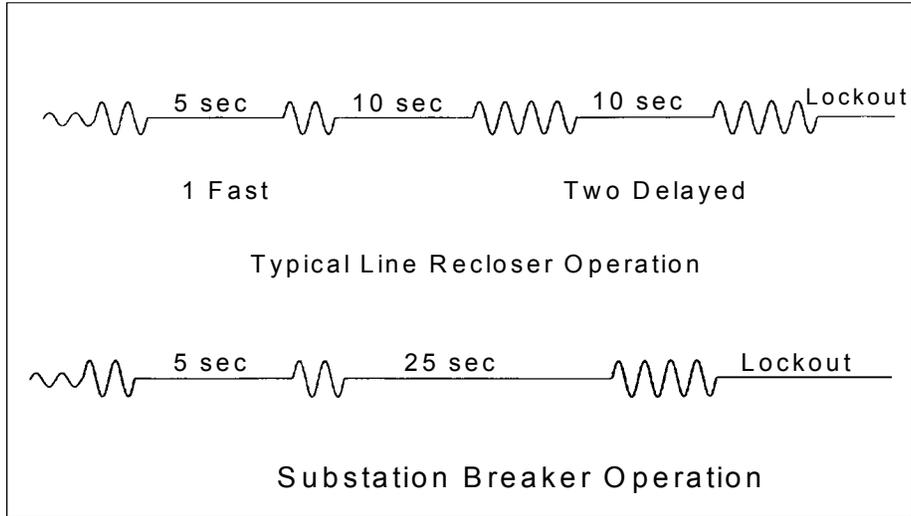


Figure 3. The most common reclosing sequences for line reclosers and substation breakers. In general, faults are to be cleared in less than 30 seconds

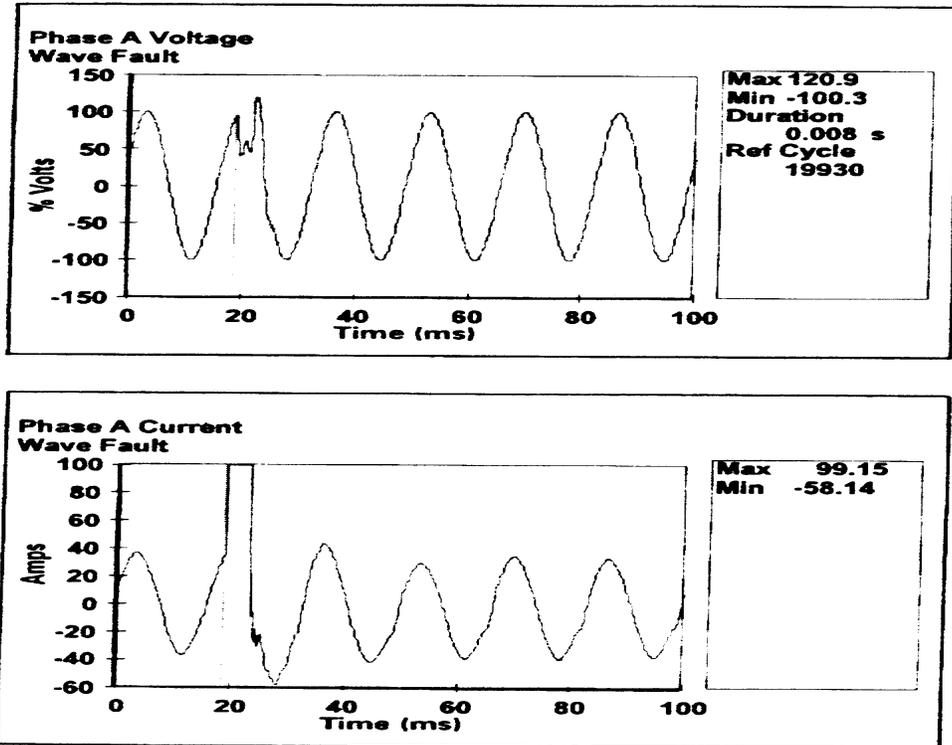


Figure 4 - Typical current-limiting fuse operation showing brief sag followed by peak arc voltage when fuse clears.

Faults on the transmission system can affect even more customers because the transmission supplies many substations. Customers hundreds of miles from the fault location can still experience a voltage sag resulting in misoperation of their equipment. Transmission faults tend to clear much faster due to the faster breaker operation. Normally, customers do not experience an interruption for a source-side transmission system fault. Transmission systems are looped or networked, as opposed to distribution systems, which are radial.

The large majority of faults on a utility system are single line-to-ground faults (SLGF). Three phase faults can be more severe, but much less common. SLGFs often result from weather conditions such as wind. Contamination of insulators, animal contact, equipment failure and accidents involving vehicles also cause faults. Although great lengths are taken to prevent faults on the system, they cannot be eliminated completely.

The magnitude of the resulting voltage during the fault will depend on the distance from the fault and source impedance. A fault close to a substation or on the transmission will result in a more significant depression in the voltage than a fault near the end of a distribution feeder. The important quantities for equipment sensitivity are the voltages at the customer bus. These voltages will depend on the transformer connections between the faulted system and the customer bus. A utility-side SLGF condition results in a much less severe voltage sag than a three-phase fault condition due to a delta-wye transformer connection in a premise.

Sensitivity of Equipment to Voltage Sags

Industrial plant power is often distributed by 3-Phase 480 V feeders. Most industrial loads are 3-phase but many small loads are single phase including much of the control circuits and computers. The voltages experienced during a voltage sag condition will depend on the equipment voltage connection. Individual phase voltages will vary, so individual loads at various voltage connections can be affected differently. This phenomena can help explain why not all loads trip when there is a fault on the utility side.

During a fault, the voltages can become unbalanced. Because the duration is so short, this is not a concern for motor heating. Different categories of equipment, different brands of equipment and even different models by the same manufacturer can and do have significantly different sensitivities to voltage sags. This is because there is no standard for voltage sag ride-through, except for SEMI F47. Since utilities in general did not measure and quantify voltage sag events, the manufacturers did not know what magnitude and duration to design ride-through capability. This lack of information has been somewhat ameliorated by a study conducted by Electric Power Research Institute (EPRI) of 25 participating utilities which included Pacific Gas & Electric Company (PG&E).

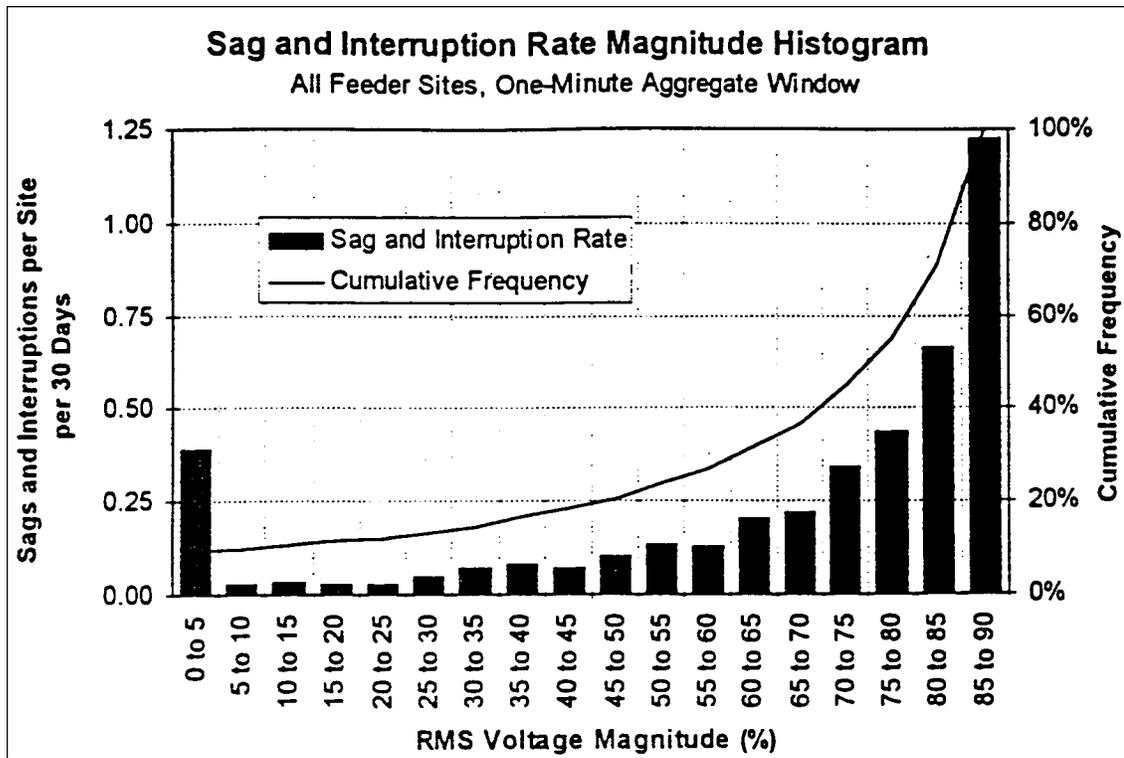


Figure 5 - Sag and Interruption Rate Magnitude Histogram, 30-day periods, One-Minute Aggregation 6/1/93 to 6/1/95, Treated by Sampling Weights, All Feeder Sites

| Voltage (%) | Sag and Interruption Rate | Frequency | Cumulative Frequency |
|-------------|---------------------------|-----------|----------------------|
| 0 to 10 | 0.42 | 9.90% | 9.90% |
| 10 to 20 | 0.06 | 1.44% | 11.34% |
| 20 to 30 | 0.07 | 1.77% | 13.11% |
| 30 to 40 | 0.15 | 3.49% | 16.60% |
| 40 to 50 | 0.17 | 4.03% | 20.63% |
| 50 to 60 | 0.26 | 6.16% | 26.78% |
| 60 to 70 | 0.42 | 9.99% | 36.77% |
| 70 to 80 | 0.78 | 18.41% | 55.18% |
| 80 to 90 | 1.89 | 44.82% | 100.00% |

Example Interpretation: From Figure 5 we can say that the average substation site in the EPRI DPQ Project experiences 1.23 incidents in which the minimum voltage during a 60-second window was between 85% and 90% of the site's base voltage, as well as 0.42 interruption incidents (less than 10% voltage). EPRI DPQ Final Report February 1996

Figure 5 is a histogram of sag and interruption rate magnitude for a two year period. Interruptions are marked by the bar labeled 0-5 remaining volts. This is a history of all 25 utilities distributed across the nation. PG&E statistics are actually much better because we do not have as many summer and tropical storms as utilities in the Midwest and along the Gulf Coast.

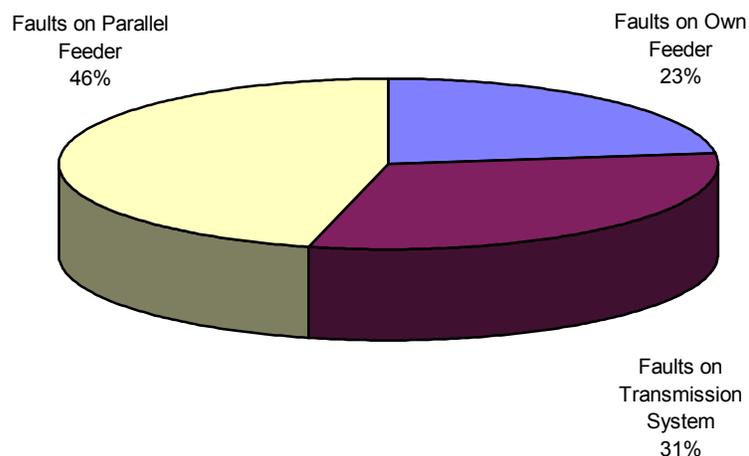


Figure 6. Causes of voltage sag events that affected the process of an industrial customer supplied from the distribution system

Figure 6 illustrates a breakdown of causes of disturbances that actually created process disruptions for one industrial customer in the EPRI DPQ project. Note that almost one-third of the problems experienced by the customer were caused by faults on the transmission system or on other distribution feeders upstream from the substation serving this customer. It is also important to note that none of these disturbances would have impacted the traditional reliability indices, since they are faults that are cleared by breaker operations with automatic reclosing (no outage lasting more than two minutes).

So how do we use this information? Semiconductor Equipment and Materials International (SEMI) is a global trade association with over 2,000 members with offices around the world including Mountain View, CA. SEMI in 1999 approved two new standards: a) SEMI F47, Specification for Semiconductor Processing Equipment Voltage Sag Immunity and b) SEMI F42, Test Method for Semiconductor Processing Equipment Voltage Sag Immunity to confirm compliance. These standards can be purchased from SEMI. See their website for information, www.semi.org. While this standard applies directly to equipment such as etching, film deposition, ion implantation, etc., it can also be applied to any process equipment.

The way that this standard will be applied is that the purchaser will specify the way the subject equipment must be manufactured and tested to meet the following sag ride-through criteria in *Table 1* and *Figure 7*. Sags that fall below the line can cause a disruption, but will not be very frequent. This is a compromise between higher equipment cost and the cost of downtime. If better ride-through is required, then it may be necessary to provide external energy ride-through mitigation equipment such as a ferroresonant transformer or a UPS.

| VOLTAGE SAG DURATION | | | | VOLTAGE SAG |
|----------------------|-------------------|-----------------|------------------|--|
| Second (s) | Milliseconds (ms) | Cycles at 60 hz | Cycles at 50 hz | Percent (%) of Equipment Nominal Voltage |
| <0.05 s | <50 ms | <3 cycles | <2.5 cycles | Not specified |
| 0.05 to 0.2 s | 50 to 200 ms | 3 to 12 cycles | 2.5 to 10 cycles | 50% |
| 0.2 to 0.5 s | 200 to 500 ms | 12 to 30 cycles | 10 to 25 cycles | 70% |
| 0.5 to 1.0 s | 500 to 1000 ms | 30 to 60 cycles | 25 to 50 cycles | 80% |
| >1.0 s | >1000 ms | >60 cycles | >50 cycles | Not specified |

Table 1.

Duration of Voltage Sag in Seconds

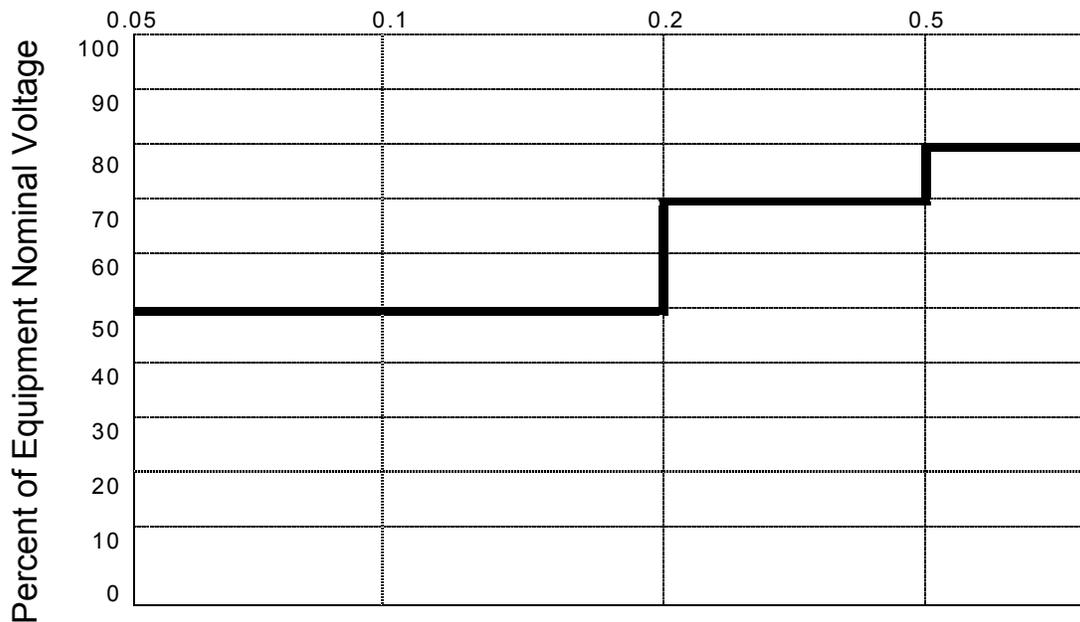


Figure 7 - Required Semiconductor Equipment Voltage Sag Ride-Through Capability Curve
Note: Equipment must continue to operate without interrupt during voltage above the line.

Examples of equipment sensitivity

Chiller controls can have 20 or so elements in the ladder logic, any one of which can trip the chiller. One can be current unbalance. Another one could be a process controller that trips at 80% voltage magnitude, regardless of the duration.

Electronic chip testers are complex devices that often require 30 minutes or more to restart. In addition, components involved in the testing process can be damaged, causing failure of internal electronic circuit boards in the testers as much as several days later. A chip tester consists of a collection of electronic loads, printers, computers, monitors, etc. If any one component of the total package goes down, the entire testing process is disrupted.

DC drives are used in many industrial processes; including printing presses, plastics manufacturing and cable manufacturing. During a sag, the controls to the dc drives and winders may trip. Interruptions can cause very expensive cleanups and restarting requirements. What makes this industrial application particularly difficult is the fact that many machines are linked together and must run in a synchronous manner. Some of these processes are sensitive to sags to only 88% of nominal. This means maybe 5 to 10 trips per year based on the utility average EPRI study.

Programmable Logic Controllers (PLC) may be in control of an entire process. Not only is it sensing the voltage but its power supply may be particularly sensitive. Since there is no approved standard, the sensitivity varies considerably from ride-through down to 50% to supersensitive PLC that will trip at a voltage below 90% for just a few cycles. Most manufacturers do not test their equipment for sag ride-through. The purchaser should start requiring the testing of new equipment.

Some machine tools can be very sensitive to voltage variations. Often robots or complicated machines are used in the cutting, drilling, and metal processing required when specialized parts are produced. Any variation in voltage can affect the quality of the part that is being machined.

Some machine tools are intentionally made sensitive to voltage variations for safety reasons. Robots generally need very constant voltage to operate properly and safely. Any voltage fluctuations, especially sags, may cause unsafe operation of the robot or machine. Therefore, these types of machines are often set to trip at voltage levels of only 90% of nominal voltage.

Several things can be done by the utility, customer, and equipment manufacturer to reduce the number and severity of voltage sags and to reduce the sensitivity of equipment to voltage sags. *Figure 8* illustrates four solution alternatives. Utility solution costs range around \$1 million per megawatt. Enhanced equipment specifications cost a few dollars because the sensitive parts have very low current ratings.

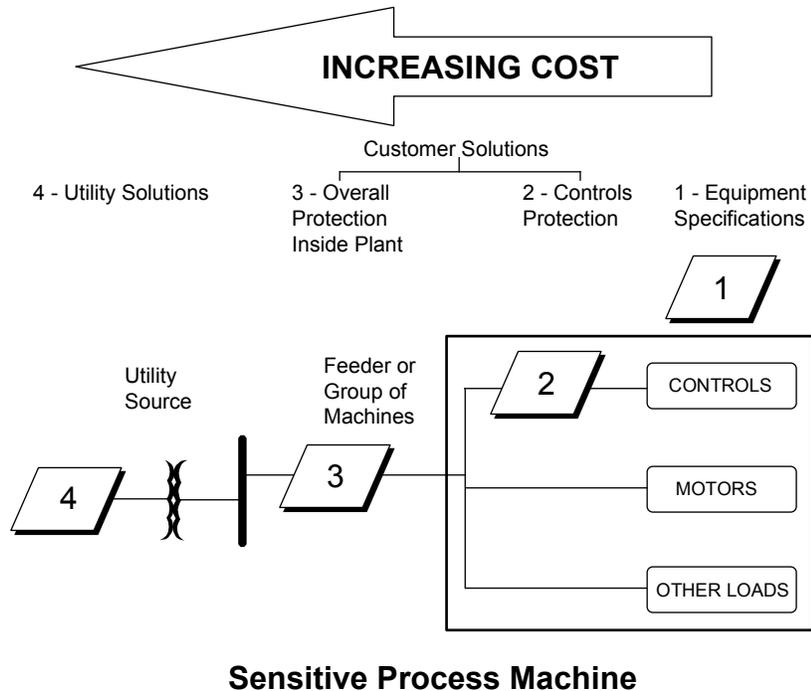


Figure 8, Four Approaches for voltage sag ride-through.

Utility Solutions

Utilities have two basic options to continue to reduce the number and severity of faults on their system:

1. Prevent faults
2. Modify fault clearing practices.

Fault prevention activities include trimming trees, adding line arresters, washing insulators, and adding animal guards. Fault clearing practices are harder to implement. Reconfiguring the circuit protection or eliminating the fast trip curve are sometimes possible. These practices may reduce the number and/or duration of momentary interruptions and voltage sags, but utility faults can never be eliminated completely.

Customer Solutions

The EPRI Power Electronics Application Center recently published and recorded some documents on tests performed on over 30 semi-conductor fabrication tools. The results of these tests indicate that retrofitting small components within the tools can dramatically increase the sag ride-through capability. The number one culprit was the “emergency-off” relay. The second most common sensitive component was a contactor. The third most common sensitive component was the power supply to PLC or any other dc logic.

The test identified two approaches to extend voltage sag ride-through. The least expensive approach is for the manufacturer to embed the solution into the design of

the machine. The more expensive approach, but a necessary one until manufacturers respond to user demands, is to provide some form of selective power conditioning. A very simple solution found was to make sure that the machine/tool and all its components are operating at the rated voltage. If a power supply, relay, or contactor is supplied with less than the required rated voltage, then the unit will be more sensitive to voltage sags. It is very important to pay close attention to the tap positions on all transformers. It may be sufficient to simply “tap up” a transformer to improve ride-through. Another very simple solution was to use phase-to-phase voltage for controls instead of phase-to-neutral.

Some manufacturers use or recommend the use of a phase monitoring relay to monitor the phase rotation, voltage magnitude and unbalance. Some are preset and some have variable thresholds. These can be counterproductive if they result in nuisance tripping. For sure do not use in the EMO circuit.

Customer solutions usually involve power conditioning for sensitive loads. Proper application of power conditioning equipment requires an understanding of the capabilities of the device. Also important is the knowledge of the specific requirements of the sensitive load and the frequency of occurrence of the problem.

Two companies have come up with a new idea to improve the ride-through performance for motor/machine starters/controllers. The solution is a small, inexpensive (under \$100) electrical device that gets inserted in series with the hold-in coil, (*see figure 9*). During a voltage sag, the device maintains a current flow through the coil that is sufficient to hold in the contacts closed. The circuit is designed to provide current to hold in the coil for sags down to 15-25% voltage. It is not designed to hold in the coil for cases where the voltage goes below 15%. This allows “emergency stop” circuits to act correctly and will prevent any problems with out-of-phase conditions following an interruption. SCR Controls, Inc. make a device called KNOWTRIP. They are located in Matthews, North Carolina. Their webpage URL is www.scrcontrols.com. Power Quality Solutions, Inc. make a device called Coil-Lock. They are located in Knoxville, Tennessee. Their webpage URL is www.pqsi.com.

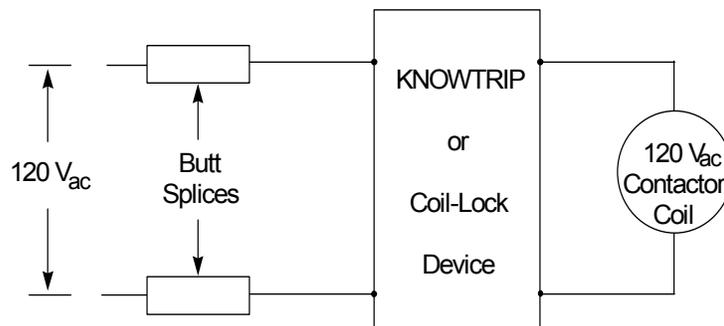


Figure 9 Inserting the hold-in circuit device in series with a motor contactor coil

Single Loop Process Controller

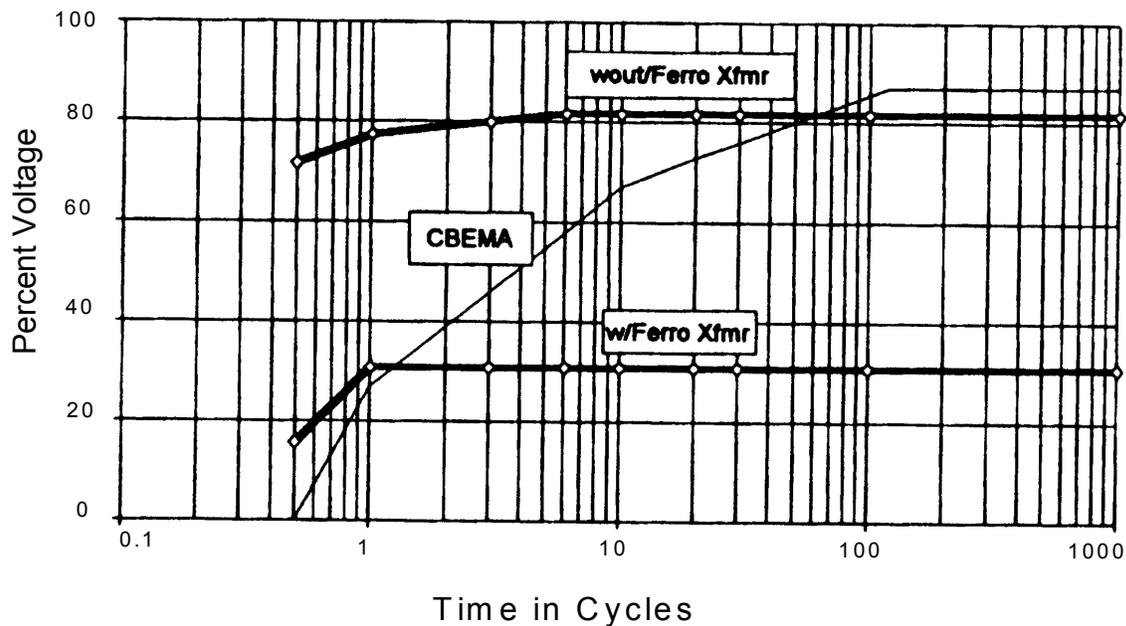


Figure 10 - Voltage Sag Improvement with Ferroresonant Transformer

Figure 10 illustrates the improvement in sag ride-through when a ferroresonant transformer is used with a single loop process controller. Essentially, the controller can ride through any sag down to 30% of nominal. Statistically, this is almost a 90% solution. Of course, ferroresonant (CVT) transformers are still available but are larger capacity and more expensive.

Depending on the type and size of the load, it may be possible to successfully isolate or filter the controls for protection. However, this is often not possible, which means that protection of the entire process is the only solution.

There are several solutions currently available that will provide ride-through capability to critical loads.

1. Motor-Generator Sets (M-G Sets), 30 to 1200 Kva three phase
2. Uninterruptible Power Supplies (UPS), any size
3. Ferroresonant, Constant-Voltage Transformers (CVT), single phase
4. Magnetic Synthesizers, three phase
5. Power Electronic devices, any size
6. Flywheels

Equipment Specifications

Embedded solutions are the most cost effective in the long run, but will be difficult to implement in the short term because manufacturers are just beginning to understand the problem. As mentioned earlier, one industry is taking steps to cure this problem--SEMI. The reason for it moving ahead is the strong association and the very high cost of disruptions.

Summary

Voltage sags are one of the most important power quality problems affecting industrial processes. The utility can improve system fault performance in a limited degree, but cannot eliminate all faults.

The customers will have to improve the ride-through capability of their sensitive equipment by either power quality mitigation equipment or embedded solutions. It will be much more economical in the long term to improve the voltage sag ride-through capability of the actual process equipment.

Adjustable speed drives (ASD) are a good example. Some manufacturers now have the capability to restart and even resynchronize the ASD output into a spinning motor. This allows use of the motor's inertia to ride through most voltage sag events.

References

IEEE Standard 1159-1995, Recommended Practice for Monitoring Electric Power Quality. This standard defines power quality terms and phenomena.

IEEE Standard 1250-1995, Guide for Service to Equipment Sensitive to Momentary Voltage Disturbances. This standard is a short overview of power quality concerns.

IEEE Standard 1100-1999, Recommended Practice for Powering and Grounding Sensitive Electronic Equipment. This recently updated standard is a thorough discussion on power quality for the serious sensitive premise.

IEEE Standard 1346-1998, Recommended Practice for Evaluating Electric Power System Compatibility with Electronic Process Equipment. This standard provides financial procedure.

IEEE Standard 493-1997, the Gold Book, chapter nine, provides procedure for predicting voltage sags.

Comment:

IEEE Standard 1346-1998 provides a procedure to calculate the financial impact of sags to a particular premise given a set of equipment and a documented history of voltage sags. The end user must quantify the cost of each shut down including: lost time, lost product, damage, etc. The end user must also have the sag history for a sufficient period of time to be statistically valid.